13

Radiological Dose Assessment

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Introduction

Radiological doses to the public result from both natural and man-made radiation. The total dose received by individuals and populations can be determined by measurements and calculations. This chapter describes LLNL's radiological dose assessments, made to determine the impact of LLNL operations, and contains a discussion of the analyses performed to demonstrate LLNL's compliance with the radiological National Emission Standards for Hazardous Air Pollutants (NESHAPs; 40 Code of Federal Regulations [CFR] 61 Subpart H).

Background Information

Because this chapter is written for a diverse readership, from scientists and regulators to interested citizens with limited scientific training, some description is given of concepts, methods, tools, and other basic material in the first three sections, as well as in two "supplements" at the end of the chapter. Supplement 13-1: "Radiation Basics," covers the different sources and types of radiation and the units used to quantify it, and it provides perspective on the wide range of radiation levels people commonly encounter. Supplement 13-2: "Radiation Control Measures at LLNL," sketches the standard operating procedures used to protect employees and the public from uncontrolled releases and unsafe levels of radiation. Readers desiring to go directly to the chapter's principal results can turn to the section on "Radiological Doses from 1998 Operations."

Releases of Radioactivity to Air

Air releases are by far the major source of public radiological exposures from LLNL operations. In contrast, releases to ground, surface, and sewerable waters are not sources of direct public exposures, since these waters are not directly consumed or used by the public. Water releases can cause indirect exposures, which are treated as special cases; for example, a recent case considered the possible dose to the public from inhalation and ingestion of soil contaminated by sewer effluent containing radioactivity

(U.S. Department of Health and Human Services 1999). Apart from such unusual occurrences, measurements and modeling of air releases determine LLNL's radiological dose to the public.

Data are gathered by three principal means: routine surveillance air monitoring for radioactive particles and gases, both on and off Laboratory property (described in Chapter 5); continuous monitoring of stack effluent at selected facilities at the Livermore site (described in Chapter 4); and usage inventories at all noncontinuously monitored or unmonitored facilities housing radioactive materials management areas and for radioactive materials used in explosive experiments at Site 300 (usage inventories are described in LLNL's NESHAPs annual reports [e.g., Biermann et al. 1999]).

Despite this "air emphasis," it should be noted that LLNL's extensive environmental monitoring program embraces all media and a wide range of potential contaminants, not limited to radioactive ones. In addition to air and the three categories of water already mentioned, the Laboratory samples soil, sediment, vegetation, and foodstuff, and measures environmental (gamma) radiation. Monitoring has been described extensively since 1971 in LLNL's environmental reports (e.g., Harrach et al. 1998; see also Chapters 4 through 11 in the present report) and in LLNL's triennially updated *Environmental Monitoring Plan* report (e.g., Tate et al. 1995) and its associated procedures and guidance documents.

Air Dispersion and Dose Models

Calculational models are needed to describe the transport and dispersion in air of contaminants and the doses received by exposed persons. Various factors dictate this need for modeling: (1) the amounts of LLNL-generated radioactive material dispersed into the atmosphere cause doses thousands of times smaller than those caused by natural background radiation (arising from irradiation by cosmic rays, inhalation of radon gas, exposure to radioactive materials in soil and rock, and ingestion of naturally occurring radionuclides present in our food and water; see Supplement 13-1), so it is difficult to demonstrate compliance with standards through physical measurements alone; (2) all potentially significant exposure pathways need to be taken into account when estimating dose impacts; and (3) the U.S. Department of Energy (DOE) and the U.S. Environmental Protection Agency (EPA) sanction the use of specific computer codes that implement their approved dosimetry and dispersion models for evaluating potential doses to the public from both routine and unplanned releases. Other advantages of a well-developed modeling capability include its utility in source design

and optimization (e.g., estimating effects of hypothetical and/or dangerous sources) and in interpreting past events (e.g., in dose reconstruction).

The computer programs we use to model air releases and their impacts feature idealized gaussian-shaped plumes and can be run on personal computers. The CAP88-PC code (Parks 1992), in particular, incorporates dosimetric and health effects data and equations that are mandated by EPA to be used in compliance assessments. Furthermore, CAP88-PC accommodates site-specific input data files to characterize meteorological conditions and population distributions for a collective dose evaluation, and the code is relatively easy to use and understand. For these reasons it has been the "workhorse" calculational tool for LLNL's regulatory compliance assessments since its availability in April 1992, particularly as applied to gradual releases occurring in the course of routine operations.

Radiation Protection Standards

The release of radionuclides from operations at LLNL and the resultant radiological impact to the public is regulated by both DOE and EPA.

DOE environmental radiation protection standards, provided under the authority of the Atomic Energy Act of 1954 and the DOE Organization Act of 1977 (both as amended), are defined in DOE Order 5400.5, *Radiation Protection of the Public and the Environment*. The standards for controlling exposures to the public from operations at DOE facilities that are incorporated in this order are based on recommendations by the International Commission on Radiological Protection (ICRP). The radiological impact to the public is assessed in accordance with DOE Order 5400.1, *General Environmental Protection*. Current indices and links to DOE orders appear on the Department of Energy Directives website (U.S. Department of Energy 1998c).

The primary DOE radiation standards for protection of the public are 1 millisievert per year (1 mSv/y) or 100 millirem per year (100 mrem/y) whole-body effective dose equivalent (EDE) for prolonged exposure of a maximally exposed individual in an uncontrolled area and 5 mSv/y (500 mrem/y) EDE for occasional exposure of this individual. (EDEs and other technical terms are discussed in Supplement 13-1 and defined in the glossary of this report.) These limits pertain to the sum of the EDE from external radiation and the committed 50-year EDE from radioactive materials ingested or inhaled during a particular year that may remain in the body for many years.

Radionuclide emissions to the atmosphere from DOE facilities are further regulated by the EPA, under the authority of Section 112 of the Clean Air Act. Subpart H of

NESHAPs under 40 CFR Part 61, sets standards for public exposure to airborne radioactive materials (other than radon) released by DOE facilities; radon is regulated by Subparts Q and T. NESHAPs implements the dosimetry system recommended by the ICRP in Publication 26 (International Commission on Radiological Protection 1977).

The EPA's radiation dose standard, which only applies to air emissions, limits the EDE to members of the public caused by activities/operations at a DOE facility to 0.1 mSv/y or 100 μSv/y (10 mrem/y). EPA regulations specify not only the allowed levels, but also specify the approved methods by which airborne emissions and their impacts must be evaluated. With respect to all new and/or modified projects, NESHAPs compliance obligations define the requirements to install continuous air effluent monitoring and to obtain EPA approval for startup of operations. NESHAPs regulations require that any operation with the potential to produce an annual-averaged off-site dose greater than or equal to 1 μSv/y (0.1 mrem/y), taking full credit for emission-abatement devices such as HEPA filters, must obtain EPA approval prior to startup of operations. This same calculation, but without taking any credit for emission abatement devices, determines whether or not continuous monitoring of emissions to air from this project is required. These requirements are spelled out in Chapter 12, "Air Quality Compliance," in LLNL's *Environmental Compliance Manual* (Lawrence Livermore National Laboratory 1996b); this report can be accessed electronically at http://www.llnl.gov/es_and_h/crosswalk.html#ecm.

Reporting Requirements

All DOE facilities that conduct significant environmental protection programs are required by DOE to prepare an annual environmental report for the site, covering activities of the previous calendar year involving releases to all media via all pathways. Because DOE facilities and operations are subject to the regulatory requirements of EPA, in particular 40 CFR Part 61, Subpart H, DOE facilities are further required to submit an annual report to the EPA, via DOE, showing compliance with NESHAPs (addressing only releases to air). Other reporting requirements address "environmental occurrences," quality assurance program documentation, and other activities.

For details on reporting requirements and citation of pertinent DOE orders and federal regulations, the reader can consult the chapter on radiological dose assessment in earlier environmental reports (e.g., Harrach et al. 1998), which are accessible in hardcopy or on the Internet at the address http://www.llnl.gov.saer, or LLNL's radiological dose assessment guidance document (Harrach 1998).

Evaluation of Sources of Radioactive Emissions

The starting point for an assessment of radiological dose is to identify and properly characterize all significant sources of radioactive emissions at a site. LLNL's sources are determined in three principal ways: (1) by an inventory process, (2) by direct measurement of the emission rate at the source (continuous effluent monitoring), and (3) by monitoring airborne gases and particulate matter at selected field points in and around the site (continuous surveillance air monitoring).

Inventoried Sources

Radioactive materials management areas (RMMAs) are areas where radioactive materials are used or stored, or where activation products occur. Several RMMAs at the Livermore site have effluent monitoring systems in place in their exhaust pathways, allowing a direct measurement of their emission rates. For unmonitored or noncontinuously monitored RMMAs, source terms for potential releases are inferred from radionuclide inventories, in accordance with EPA methods.

Experimenters and facility managers provide inventory data following a protocol designed and administered by LLNL's Environmental Protection Department. A full (100%) inventory is conducted every three years; only the "key" Livermore site facilities, defined as those in a ranked list that collectively accounted for 90% or more of the previous year's Livermore site radiological dose to members of the public, are reinventoried annually. LLNL conducted complete radionuclide inventories for operations in 1994 and again in 1997. In addition, all new RMMAs (ones that commenced operations in the year under evaluation) are inventoried, and radionuclide inventories for all Site 300 explosives experiments are newly evaluated each year. A description of LLNL's inventory process, including examples of the inventory form and accompanying instructions, is given in the guidance document for preparation of NESHAPs annual reports (Gallegos et al. 1998b).

For dose-assessment modeling of unmonitored or noncontinuously monitored sources, the effective emission rate is calculated from radiological usage inventories by applying EPA-specified fractions for potential release to air of materials in different physical states (solid, liquid, powder, or gas) for each radioisotope. The inventory quantity (in becquerels or curies) is multiplied by a state-dependent release fraction to give the potential annual release to air, i.e., the "effective" emission rate, in accordance with 40 CFR Part 61, Appendix D. If the material is an unconfined gas, the release fraction is 1.0; for liquids and powders, 1.0×10^{-3} is used; and for solids, 1.0×10^{-6}. In this same spirit, if the radioactive material is encapsulated or sealed for the entire year (i.e., it was

not used and release to air was prevented), then its release fraction is considered to be zero. For materials that were encapsulated or sealed for part of the year, or that resided in different facilities over the course of the year, "time weighting factors" are introduced to properly account for the release potential. Data on inventories and descriptions of the diffuse sources can be found in the guidance document (Gallegos 1998) and in NESHAPs annual reports for 1993 through 1998 (Harrach et al. 1994; Surano et al. 1995; Gallegos et al. 1996; Gallegos and Biermann 1997; Gallegos et al. 1998a; and Biermann et al. 1999).

Monitored Sources

Stack Effluent Monitoring

Actual measurements of radionuclides in effluent flow are the basis for reported emissions from continuously monitored sources. In 1998, eight buildings at the Livermore site had continuously monitored discharge points: Buildings 175, 177, 251, 292, 331, 332, 490, and 491. The monitoring systems are described in the LLNL *NESHAPs 1998 Annual Report* (Biermann et al. 1999), and in Chapter 4: "Air Effluent Monitoring," in this report. Taken together, these buildings feature about 100 continuously operating monitors.

The most significant monitored source in terms of public dose impact is the Tritium Facility, Building 331, at the Livermore site. Each of the two 30-m stacks on this facility has both a continuous-monitoring ion-chamber alarm system and continuous molecular-sieve samplers (see Chapter 4 in the Data Supplement). The sieve samplers, which can discriminate between tritiated-water vapor (HTO) and molecular tritium (HT), provide the values used for environmental reporting. The alarmed ion chambers provide real-time tritium concentration release levels (HT plus HTO). Monitoring of these stacks provides an accurate measure of the total quantity (in becquerels or curies) of tritium released to the environment, time-resolved over the course of the year. Since the stacks have known properties (height, flow rate, and diameter) and the wind field properties (wind speed, direction, and fluctuation characteristics) are continuously monitored, these data are optimal inputs to modeling. The quality of data on source emission rates, emission conditions (such as stack height, diameter, and flow velocity), and wind patterns affects the accuracy of air dispersion and dose assessment modeling more than any other input factor.

Discharge points at Buildings 175, 177, 251, 292, 332, 490, and 491 are monitored for gross alpha and gross beta radioactivity. In contrast to monitoring unabated tritium gas

effluent in the Building 331 stacks, air samples for particulate emissions are extracted downstream of high-efficiency particulate air (HEPA) filters and prior to the discharge point to the atmosphere. Particles are collected on membrane filters. Sample results are generally found to be below the minimum detectable concentration (MDC) of the analysis; for details, consult Chapter 4 in this report, and the 1998 NESHAPs annual report (Biermann et al. 1999).

Among the eight continuously monitored facilities at the Livermore site, probably only the Plutonium Facility (Building 332) requires monitoring under the EPA's 0.1 mrem/y standard alluded to earlier in the subsection on radiation standards. The other seven are continuously monitored for programmatic or other reasons. For example, continuous monitoring is maintained at the Tritium Facility to provide the most direct and accurate measure of its release of tritium to the atmosphere, and continuous monitoring is maintained at the Heavy Elements Facility (Building 251) in lieu of undertaking a modeling and measurement effort that would be required to demonstrate that monitoring is not needed.

Dose calculations based on effluent monitoring data are expected to be considerably more accurate than those relying on usage-inventory data, physical state release-to-air fractions, emission-abatement factors, and time factors.

Surveillance Air Monitoring

To provide wide-area coverage complementing the narrowly focused stack effluent monitoring, surveillance air monitors are placed at selected locations on and in the vicinities of the Livermore site and Site 300 to detect radioactive gases and particulate matter in ambient air. In addition, dose rates from external penetrating radiation (gamma rays) are measured using thermoluminescent dosimeters (TLDs). Siting of the air monitors and TLDs is done in accordance with the LLNL *Environmental Monitoring Plan* (Tate et al. 1995). Surveillance air monitors are also placed in the vicinity of known diffuse (extended area) emission sources at the Livermore site, specifically those associated with Buildings 292, 331, 514, and 612. Such monitors are also located in and around the Livermore site's southeast quadrant, and in on-site locations providing wide coverage of Site 300. These special monitors measure the concentrations of radionuclides present in the air near the sources and allow a direct determination of their environmental impact; see Chapter 5 in this report. In addition to their utility in connection with releases from routine operations, the surveillance air monitors have proven valuable in quantifying the magnitude of accidental releases and their dose impacts.

Determinations of Dose

This section briefly describes the way LLNL estimates doses to the public for compliance purposes, touching on the main modeling approaches, identifying the key hypothetical receptors that represent the most exposed public individuals, discussing some important aspects regarding the modeling of tritium, and briefly noting some of the special modeling challenges raised by diffuse sources and explosives experiments.

Principal Modeling Approaches

LLNL's primary calculational tool for estimating dose and risk to the public from routine operations and most unplanned releases is the computer code CAP88-PC. The user's guide (Parks 1992) provides useful information on the code, including discussions of the basic equations and key input and output files. Additional information, e.g., about LLNL-site-specific data files and several important caveats on use of the code, has been presented in earlier environmental reports (e.g., Harrach et al. 1998) and more fully in the LLNL radiological dose assessment guidance document (Harrach 1998).

Other codes such as EPA's INPUFF code (Peterson and Lavdas 1986) or the HOTSPOT code (Homann 1994) are used as needed to address unplanned releases or transient releases from normal operations or accidents. Many other gaussian-plume-type computer models are available; see for example, the annotated lists in *Atmospheric Dispersion Modeling Resources* (Oak Ridge 1995) and *Supplement B to the Guideline on Air Quality Models* (U.S. Environmental Protection Agency 1993).

A complementary approach to deriving effective dose equivalents (EDEs) using the built-in dosimetry model in CAP88-PC or other codes is to explicitly calculate them using mathematical formulas from, e.g., the Nuclear Regulatory Commission's Regulatory Guide 1.109 (1977), which incorporate dose conversion factors consistent with those in the International Commission on Radiation Protection's document number 30 (1980). This approach, outlined in Appendix A of this report, has been used historically at LLNL (preceding the availability of CAP88-PC), and continues to be used to evaluate annual doses to the public inferred from sampling of local environmental media (air, water, vegetation, and wine).

Identification of Key Receptors

When assessing probable off-site impacts, three potential doses are emphasized. First is the dose to the "site-wide maximally exposed individual member of the public,"

(SW-MEI; defined below and in the glossary). Second is the dose to the maximally exposed individual (MEI) member of the public from a given emission point. Third is the collective or "population dose" received by people residing within 80 km of either of the two LLNL sites, adding the products of individual doses received and the number of people receiving them.

The SW-MEI is defined as the hypothetical member of the public at a single publicly accessible location (where members of the public reside or abide) who receives the greatest LLNL-induced EDE from all sources at a site (e.g., the Livermore site). This dose sums the contributions of all emission points for evaluation under the EPA's 100 μSv / y (10 mrem / y) standard. Public facilities that could be the location of the SW-MEI include schools, churches, businesses, and residences. This hypothetical person is assumed to reside at this location 24 hours per day, 365 days per year, continuously breathing air having the ground-level radionuclide concentration, and consuming a specified fraction of his or her food and drinking water that is affected by the releases of radioactivity from the site. Thus, the SW-MEI dose is not actually received by any actual individual and should be viewed as a health-conservative estimate (i.e., over-estimate) of the highest possible dose to any member of the public. The location of the SW-MEI is sensitive to the frequency distribution of wind speeds and directions and locations of key sources in a given year and can change from one year to the next. At the Livermore site, the SW-MEI currently is located at the UNCLE Credit Union, about 10 m outside the controlled eastern perimeter of the site. This location lies 948 m from the principal radionuclide source, the Tritium Facility (Building 331), in an east-northeast direction (the typical prevailing wind direction). At Site 300, the SW-MEI currently is located in an experimental area termed "Bunker 2" operated by Primex Physics International. Bunker 2 lies about 300 m outside the east-central boundary of Site 300, 2.38 km east-southeast of the principal firing table at Building 801.

The location of the MEI is generally different for each emission point; the MEI dose is used to evaluate whether continuous monitoring of each particular emission point is required under a 1 μSv / y (0.1 mrem / y) standard (1% of the EPA standard for allowable dose to the SW-MEI); no credit for emission abatement devices is permitted in making this determination. A related dose frequently needed is identical to the MEI dose, except that credit *is* allowed for abatement devices that are in place; this dose determines the necessity to petition the EPA for permission to start up an activity (new or modified project) that would cause a dose of 1 μSv / y (0.1 mrem / y) or more to the MEI.

Doses in this second category, with and without allowance for abatement, are a main concern when new projects or changes to existing projects (in which releases of radioactivity to the environment may occur) are reviewed for joint compliance with

NESHAPs and the National Environmental Policy Act (NEPA). The possible environmental and worker safety issues raised by each proposed activity or project are examined from several different points of view in a process coordinated by LLNL's Environmental Protection Department, including a review and evaluation of potential emissions of radionuclides and air toxics. Air quality compliance requirements for projects are described in Chapter 12 of LLNL's *Environmental Compliance Manual* (1996).

Assessment Assumptions Regarding Tritium

Several aspects of tritium dose estimates based on CAP88-PC should be noted.

Relative Contributions to Dose from HTO and HT Emissions

Tritium (H-3) emissions account for the major dose from operations at the Livermore site. These emissions exist in two major chemical forms: tritium oxide or tritiated water vapor (HTO) and tritium gas (HT). The doses received by exposure to these two forms differ greatly. HTO enters the body by ingestion, inhalation, and dermal absorption. Ingested HTO is distributed throughout the entire body and eliminated at the same rate as body water. Inhaled HTO dissolves in the fluids of the lung and is absorbed. HT enters the body via inhalation, and very little is retained, most being exhaled. The effective dose equivalent from inhalation of tritium gas is lower by a factor of about 25,000 than that from tritium oxide inhalation (Eckerman et al. 1988). HT requires conversion to HTO (oxidation) to produce significant dose. Such conversion in air during plume transport and in soil and vegetation following deposition is a complicated process.

Emissions of HTO are expected to be the major contributor to the tritium dose, particularly for nearby individual receptors such as the MEI and SW-MEI, and we typically input to CAP88-PC only the curies of HTO released to air, disregarding the HT component. A more conservative approach would be to treat all HT as HTO in dose calculations. Recently, EPA has mandated that LLNL do exactly that when calculating dose to the public for NESHAPs compliance purposes; for a discussion of this issue and the dose impacts, see the *LLNL NESHAPs 1998 Annual Report* (Biermann et al. 1999). The result of treating HT as HTO for the 1998 assessment, for which Tritium Facility emissions were divided between 85 curies of HTO and 25 curies of HT, was to increase the Livermore site dose to the SW-MEI by about 12% compared to the value obtained using our usual procedure. The population dose from Livermore site operations, which gives greater weight to high-stack emissions, was increased by 24%. As in previous years, this report emphasizes doses excluding contributions from HT because we believe it is more accurate to do so than to represent HT as fully converted to HTO, and to provide continuity with doses reported in the past. In addition, we provide the dose as calculated for the EPA.

Dose-rate Conversion Factor for Tritium

The dose-rate-conversion factor that CAP88-PC uses for inhalation-plus-dermal-absorption of tritium is outdated and more conservative than values quoted in recent literature. In 1980, the ICRP in its publication ICRP 30 (1980) recommended that skin intake should be 50% of lung intake, revising its earlier recommendation stated in ICRP 2 (1959) that skin intake equals lung intake. The CAP88-PC dose-rate-conversion factor for tritium contains the 1959 recommendation, producing an inhalation-plus-dermal-absorption dose that is too large by a factor 4/3 relative to the more recent recommendation; see Attachment 3 in the *NESHAPs 1995 Annual Report* (Gallegos et al. 1996).

Overestimate of Ingestion Dose for Tritium

Finally, CAP88-PC overestimates the ingestion dose from tritium in a manner that depends on input selections, according to a recent article by Barry Parks (Parks 1999). The cause can be traced to three key assumptions implicit in the software that may not be immediately apparent to the user: (1) the contribution of home-grown food, (2) the distances at which food is produced, and (3) the number of people consuming locally produced food. Documentation on how these overestimates can occur is also available on the Internet at the address http://www.er.doe.gov/production/er-80/cap88/tritium.html.

Special Modeling Problems

Nonstack releases may require special measurements and calculations to characterize the source. Both the Livermore site and Site 300 provide important examples in this regard.

Diffuse Sources

Nonstack releases often fall into the classification of "diffuse sources." One example is leakage of tritium-contaminated water from an underground tank at Building 292 at the Livermore site, which results in the release of tritium to the atmosphere via soil moisture evaporation and root-uptake and transpiration by plants, from one pine tree in particular. A discussion of this source appears in the section on "Livermore Site Diffuse Sources" in the *NESHAPs 1993 Annual Report* (Harrach et al. 1994), and subsequent NESHAPs annual reports provide updates. Emissions from certain difficult-to-characterize sources sometimes can be inferred from data obtained by LLNL's routine surveillance air monitoring program, in which the ambient air at selected locations within and outside of Laboratory boundaries is continuously monitored for tritium gas

and radioactive particles. An example in this category is provided by the operations in the Building 612 waste storage yard at the Livermore site, which are characterized using data from an air monitor in the yard. Another example is the diffuse source caused by resuspension of depleted uranium in soil at Site 300; an air monitor at the location of the SW-MEI measures the annual-average concentration of uranium in air. A theoretical model described in the *NESHAPs 1995 Annual Report* (Gallegos et al. 1996) was developed to distinguish between the contribution made to these Site 300 data by LLNL-operations-contributed uranium, compared to the considerably larger contribution from naturally-occurring uranium. The routine air surveillance monitoring program also has been particularly useful in registering the magnitude of unplanned releases; an example of this type is provided by the accidental release of curium-244 from Building 513 in 1997, discussed in the Executive Summary, Chapter 2, and Chapter 12 of last year's environmental report (Harrach et al. 1998), as well as in last year's NESHAPs annual report (Gallegos et al. 1998).

Modeling Dose Impacts from Explosives Experiments at Site 300

Modeling releases of radionuclides into the atmosphere from explosive tests at Site 300 requires special consideration compared to conventional stack or area sources. During experiments, an explosive device containing depleted uranium is placed on an open-air firing table and detonated. A cloud of explosive decomposition products forms promptly (on a roughly 1-minute time-scale) over the firing table, typically reaching a height of several hundred meters, and disperses as it is carried downwind. (The depleted uranium does not contribute to the explosive energy, which is entirely of chemical origin.) In the absence of measurements of the properties of the cloud, we assume for compliance modeling purposes that it instantaneously reaches an initial height and size governed by known empirical scaling laws for detonations, in which the scaling parameter is the TNT-equivalent explosive mass. The specific equations we use for the maximum elevation, H_{max}, reached by the plume and the diameter, D, of the cloud of decomposition products have been described elsewhere (Harrach et al. 1998, Harrach 1998).

This prescription provides the initial condition for a cloud whose subsequent motion is modeled using a gaussian plume air dispersion code. A puff-code-based modeling methodology that would treat these transient explosive events as short-duration bursts or puffs, and which would incorporate some of the effects of the hilly terrain at Site 300, was submitted to EPA for approval in 1992 (Biermann et al. 1993). EPA decided that, from the standpoint of regulatory compliance, the use of CAP88-PC to model these explosives experiments was adequate, despite the recognized difficulties. CAP88-PC simulates each explosive experiment or shot as a continuous, year-long, stack-type emission (i.e., the total activity released in a time period of order one minute in the

explosion is treated as though it were released gradually over the course of an entire year), with meteorological data corresponding to annual-average conditions at Site 300. As inputs to the code, the scaling results for H_{max} and D are used as the fixed plume height and the stack diameter.

Isotopic ratios for depleted uranium are used. The masses of the three uranium isotopes with atomic weights 238, 235, and 234 in depleted uranium occur in the weight-percentages 99.8, 0.2, and 5×10^{-4}, respectively. The inventory for each explosive experiment specifies the mass of depleted uranium used: M_{DU}(kg). Multiplying this quantity by the respective specific activities gives the total number of curies for each isotope in the cloud. For example, the fraction by weight of U-238 in depleted uranium is 0.998, and its specific activity is 3.33×10^{-4} Ci/kg, giving 3.33×10^{-4} (Ci/kg) $\times$ M_{DU}(kg) as the number of curies of U-238 in the cloud. The corresponding values for U-235 and U-234 are 4.29×10^{-6} (Ci/kg) $\times$ M_{DU}(kg) and 3.10×10^{-5} (Ci/kg) $\times$ M_{DU}(kg), respectively.

In the absence of detailed data about the explosive experiments, we make several highly conservative assumptions in our calculations. We assume that (1) 100% of the depleted uranium present in the experiment is completely aerosolized and dispersed as a cloud; (2) the median particle size is the CAP88-PC default value of 1 μm; (3) the lung clearance class for inhaled material is class Y. (Note: Clearance of inhaled material from the lung to the blood or to the gastrointestinal tract depends on the chemical form [e.g., U_3O_8] of the radionuclide and is classified as D, W, and Y, respectively, for clearance times of order days, weeks, and years.) These assumptions may produce a dose that is too high by a factor of 10 or more. We believe a more realistic release-to-air fraction for the uranium is no greater than 0.2, but we lack sufficient documentation to use a value other than 1.0. Also, the median particle size may be much larger than 1 μm, and a sizable fraction of the aerosolized particles might be more properly characterized by lung clearance class D, which produces a dose by inhalation of depleted uranium that is smaller by a factor of about 16 compared to class Y. Even with these assumptions, the MEI and SW-MEI individual doses, as well as the collective or population dose, that we calculate for the explosive experiments are very small (see, e.g., the Summary and Conclusions section of this chapter).

Radiological Doses from 1998 Operations

More than 200 emission points were reported on in the 1998 modeling runs. These emission sources were of several types: stacks and other exhaust pathways from buildings (including emissions from all RMMAs in which radiological operations took

place); diffuse area sources generally external to buildings; and open-air firing tables at Site 300 where explosives experiments were conducted.

The principal diffuse sources at the Livermore site in 1998 were the waste storage and drum sampling areas at Hazardous Waste Management's Building 612 Yard, a waste accumulation area (WAA) at the Tritium Facility (Building 331), Hazardous Waste Management's Tank Farm at Building 514, and the Southeast Quadrant of the Livermore site, where resuspension of contaminated soil occurs. Diffuse sources at Site 300 included the total land area on site, where evaporation of tritium and resuspension of depleted uranium can occur, and a low-level-waste staging area at Building 804. This section summarizes the main results of our calculations for 1998 operations and exhibits the trends in these results over recent years. For further details, especially regarding the diffuse sources at the two sites, see the *LLNL NESHAPs 1998 Annual Report* (Biermann et al. 1999).

Dose Breakdown by Facility

Table 13-1 lists all LLNL facilities and diffuse sources having the potential to release radioactivity into the environment during 1998. For each facility or building, the table gives the number of stacks or other exhaust avenues discharging radionuclides, lists the dose to the SW-MEI caused by the single most dominant emission point at each facility, and identifies the types of operations occurring in the building or facility or the nature of the diffuse source. Corresponding data is included for the Site 300 explosive experiments. Facilities in which no operations using radionuclides took place in 1998 or in which any radionuclides present were encapsulated or sealed for the entire year are excluded from **Table 13-1**.

The principal feature shown in the table is that LLNL has a large number of very small radioactive sources, and only a few that could be considered significant. As shown more clearly in subsequent tables, about a half-dozen sources account for nearly all of the dose to members of the public, and the total dose is quite small compared to federal standards for radiation protection of the public.

Unplanned Releases

There were no unplanned atmospheric releases at the Livermore site or Site 300 in 1998.

Table 13-1. Sources of radiation dose from LLNL releases (measured and potential) to air: stacks and other exhaust pathways from buildings containing radioactive materials management areas and diffuse area sources.[a,b]

Bldg	Facility	Potential emission points	Maximum EDE[c] (μSv/y)	Operations
	Livermore site point sources			
131	Offices and laboratories, Mechanical & Electrical Engineering	3	6.5×10^{-6}	Display of parts
132N	Offices and laboratories; Chemistry & Materials Sciences; Nonproliferation, Arms Control & International Security (NAI); and others	9	3.3×10^{-9}	Preparation of aqueous solutions and waste samples for analysis
151	Isotope Sciences; Chemistry & Materials Science Environmental Services Laboratory	27	1.5×10^{-4}	Application of nuclear and isotope sciences to a wide range of research; sample analysis of waste streams and environmental media for radionuclide content
174	Laser Isotope Separation	1	1.5×10^{-11}	Pulse laser experimentation
175	Laser Isotope Separation	6	0.0[d]	Cleaning and refurbishing of uranium parts
177	Laser Isotope Separation	8	1.2×10^{-2}	Sample preparation, cleaning of parts, processing uranium oxide powders, melting of uranium in crucibles under vacuum, liquid uranium corrosion studies
194	Physics & Space Technology	2	9.4×10^{-5}	High-energy linear accelerator (LINAC), positron beam generation and experiments
212	Physics & Space Technology	2	6.8×10^{-11}	Physics experiments, residual contamination from previous operation of rotating target neutron source (no longer operating)
222	Chemistry & Materials Science	7	5.0×10^{-6}	Chemical analyses, cleaning equipment, waste samples preparation and analysis, decontamination, x-ray fluorescence analysis, sample digestion
231	Chemistry & Materials Science, Engineering, Safeguards & Security	14	2.8×10^{-6}	Materials research and testing, metals processing and characterization, electron-beam welding, grinding/ polishing, casting, microscopy, sample preparation, storage
235	Chemistry & Materials Science	3	3.1×10^{-11}	Material structure studies, precision cutting, ion implantation, metallurgical studies, sample preparation
241	Chemistry & Materials Science	3	1.8×10^{-6}	Materials properties research and testing
251	Heavy Elements Facility, Physics & Space Technology			Storage of transuranic isotopes prior to disposal
	Seismically hardened area	4	0.0[d]	
	Unhardened areas	37	1.3×10^{-3}	

Table 13-1. Sources of radiation dose from LLNL releases (measured and potential) to air: stacks and other exhaust pathways from buildings containing radioactive materials management areas and diffuse area sources[a,b] (continued).

Bldg	Facility	Potential emission points	Maximum EDE[c] (μSv/y)	Operations
253	Hazards Control	7	3.3×10^{-8}	Chemical analyses and counting of radioactive samples
254	Hazards Control	2	1.9×10^{-12}	Bioassays, analytical services, analysis of urine for radionuclides
255	Hazards Control	2	7.4×10^{-11}	Radiation standards and instrument calibration
281	Chemistry & Materials Science	5	1.6×10^{-8}	Sample preparation, wet chemistry laboratory, tracers
282	Physics & Space Technology	1	6.2×10^{-12}	Residual tritium contamination from past activities
292	Environmental Programs	3	2.3×10^{-5}	Tritium contamination from prior operations
298	Laser Fusion Program	3	3.5×10^{-5}	Laser fusion targets research and development
321	Materials Fabrication	5	3.1×10^{-7}	Milling, shaping, heat treating, and machining depleted uranium parts
322	Mechanical Engineering	1	4.3×10^{-9}	Cleaning and plating of depleted uranium
327	Mechanical Engineering	1	1.6×10^{-7}	Nondestructive ultrasonic material evaluation
331	Tritium Facility, Defense & Nuclear Technologies	2	2.0×10^{-1}[d]	Tritium research and development, facility decontamination and decommissioning operations
332	Plutonium Facility, Defense Sciences Program	8	0.0[d]	Plutonium research
361	Biology and Biotechnology Research	13	4.6×10^{-6}	DNA labeling, sequencing, hybridization, and repair; human genome research; enzyme assay; DNA protein interaction studies
362	Biology and Biotechnology Research	2	9.5×10^{-8}	Characterization of metabolic pathways
363	Biology and Biotechnology Research	3	1.1×10^{-13}	Human urine sample project, rotary evaporation
364	Biology and Biotechnology Research	4	4.9×10^{-7}	DNA labeling and protein extraction, AMS sample preparation
365	Biology and Biotechnology Research	3	1.4×10^{-8}	Housing research animals, animal research, equipment decontamination
366	Biology and Biotechnology Research	1	5.9×10^{-8}	DNA labeling
381	Laser Fusion	1	7.0×10^{-9}	Tritium handling for laser target R&D
391	Laser Fusion	1	7.4×10^{-5}	Housing of high-energy laser; fusion target irradiation
490	Laser Isotope Separation	1	0.0[d]	U.S. Enrichment Corporation (USEC) isotope separation operations, including vaporization of uranium for enrichment
491	Laser Isotope Separation	1	0.0[d]	USEC isotope separation operations

Table 13-1. Sources of radiation dose from LLNL releases (measured and potential) to air: stacks and other exhaust pathways from buildings containing radioactive materials management areas and diffuse area sources[a,b] (continued).

Bldg	Facility	Potential emission points	Maximum EDE[c] (μSv/y)	Operations
513	Hazardous Waste Management	3	$1.9 \times 10–5$	Sampling, treatment, and storage of hazardous, mixed, and radioactive waste; process optimization and treatability studies; decontamination and decommissioning activities
514	Hazardous Waste Management (see also diffuse sources below)	2	$4.1 \times 10–4$	Waste consolidation, vacuum filtration of treated waste water
612	Hazardous Waste Management	3	$4.2 \times 10–3$	Waste sampling and treatment; laboratory analysis of waste treatment and treatability samples
625	Hazardous Waste Management	2	8.4×10^{-8}	Repackaging of wastes
	Site 300 point sources			
810A	Site 300 firing table support	1	1.2×10^{-7}	Assembly of explosives
801	Flash x-ray machine (FXR)	1	$5.2 \times 10–7$	Flash x-ray photography of explosives experiments
801	Site 300 firing table at 801	—[e]	$1.7 \times 10–1$	Detonation of explosives
851	Site 300 firing table at 851	—[e]	$1.9 \times 10–2$	Detonation of explosives
851	Linear accelerator	1	$9.6 \times 10–6$	Research
854	Tent	1	$4.7 \times 10–6$	Sampling of historical wastes
	Livermore site diffuse sources[f]	6	See next 5 entries below.	Storage areas and contaminated ground
292	Spill area	1	2.9×10^{-7}	Evaporation and transpiration of tritiated water from underground tank leakage
331	Tritium Facility (external)	1	3.9×10^{-2}	Outdoor waste accumulation area
514	Hazardous Waste Management Tank Farm	1	1.3×10^{-3}	Liquid waste processing, treatment, and storage
612	Hazardous Waste Management	2	1.9×10^{-1}	Storage of low-level waste; drum sampling and waste accumulation areas
—	Southeast quadrant of Livermore site	1	8.4×10^{-4}	Contaminated ground

Table 13-1. Sources of radiation dose from LLNL releases (measured and potential) to air: stacks and other exhaust pathways from buildings containing radioactive materials management areas and diffuse area sources[a,b] (concluded).

Bldg	Facility	Potential emission points	Maximum EDE[c] (μSv/y)	Operations
	Site 300 diffuse sources(f)	3	See next 3 entries below.	Contaminated ground and water
—	All Site 300 land area	1	3.5×10^{-4}	Evaporation of tritium from contaminated soil and water
—	All Site 300 land area	1	5.3×10^{-2}	Resuspension of uranium in contaminated soil
804	Open area	1	6.0×10^{-6}	Low-level waste staging area

a *LLNL NESHAPs 1998 Annual Report* (Biermann et al. 1999).

b RMMAs in which no operations using radionuclides took place in 1998 or in which all radionuclides were encapsulated or sealed for the entire year are not included in this table. Table entries refer to routine operations, not unplanned releases.

c The maximum effective dose equivalent to the sitewide maximally exposed individual (SW-MEI) member of the public from a single discharge point, among all discharge points modeled for the indicated facility or building. The SW-MEI is defined in the section entitled Identification of Key Receptors: MEI and SW-MEI.

d The effluents from the facility are monitored. Zeroes refer to monitored values below the minimum detectable concentration, as discussed, for example, in the "Air-Emission Data" section of the NESHAPs 1998 annual report cited in footnote a.

e Open air dispersal in 1998.

f Diffuse sources are described briefly in the section on Special Modeling Problems, and more fully in the NESHAPs 1998 annual report cited in footnote a.

Doses to Site-Wide Maximally Exposed Individuals

The 1998 calculated EDE to the SW-MEI from Livermore site point sources was 0.25 μSv (0.025 mrem). Emissions from the two 30-m stacks at the LLNL Tritium Facility (Building 331) accounted for most of this: 0.23 μSv (0.023 mrem), or about 92%. For the Livermore site, the SW-MEI dose caused by diffuse emissions in 1998 was 0.24 μSv (0.024 mrem). Combining point and diffuse sources, the total annual dose was 0.49 μSv (0.049 mrem), divided 52% by 48% between point and diffuse source emissions. This is about half of last year's total, principally reflecting decreased emissions from the stacks of the Tritium Facility (Building 331): 4.1×10^{12} Bq (110 Ci) of HTO in 1998, compared to 1.0×10^{13} Bq (270 Ci) the previous year. Calculating dose as directed by EPA, the total annual dose to the SW-MEI from Livermore site operations was 0.55 μSv (0.055 mrem), with 57% attributed to point sources and 43% to diffuse sources (see the discussion in the Assessment Assumptions Regarding Tritium section earlier in this chapter).

The calculated EDE to the SW-MEI at Site 300 in 1998 was 0.24 μSv (0.024 mrem), with 0.19 μSv (0.019 mrem) caused by emissions in the course of explosives experiments at the Building 801 and 851 firing tables. The remaining 0.053 μSv (0.0053 mrem), or about 22% of the total, was attributed to Site 300 diffuse sources; resuspension of LLNL-contributed uranium in surface soils throughout Site 300 was responsible for nearly all of this dose from diffuse sources. **Table 13-2** summarizes doses to the site-wide maximally exposed public individuals for the Livermore site and Site 300 over the past nine years.

Table 13-2. Doses (μSv) calculated for the site-wide maximally exposed individual for the Livermore site and Site 300, 1990 to 1998.

Year	Total dose	Point source dose	Diffuse source dose
Livermore site			
1998	0.49[a]	0.25[a]	0.24
1997	0.97	0.78	0.19
1996	0.93	0.48	0.45
1995	0.41	0.19	0.22
1994	0.65	0.42	0.23
1993	0.66	0.40	0.26
1992	0.79	0.69	0.10
1991	2.3	—[b]	—[b]
1990	2.4	—[b]	—[b]
Site 300			
1998	0.24	0.19	0.053
1997	0.20	0.11	0.088
1996	0.33	0.33	0.0045
1995	0.23	0.20	0.03
1994	0.81	0.49	0.32
1993	0.37	0.11	0.26
1992	0.21	0.21	—[c]
1991	0.44	0.44	—[c]
1990	0.57	0.57	—[c]

a Calculating dose as directed by the EPA, the total dose for 1998 is 0.55 μSv, and the point source dose is 0.31 μSv; see the discussion in the section on Assessment Assumptions Regarding Tritium.

b Diffuse source doses were not reported separately from the total dose for the Livermore site for 1990 and 1991.

c No diffuse emissions were reported at Site 300 for years prior to 1993.

The 1998 firing tables total is typical of values in recent years (see the "point source dose" column for Site 300 in **Table 13-2**). **Table 13-3** shows the potential public dose values attributed to firing table experiments for 1990 through 1998, correlated with the total amounts of depleted uranium and the total quantity of high explosives used each year in the experiments. (Only experiments that included depleted uranium are considered; most have none.) The data show that variations from year to year in these doses mainly correspond to differences in the amount of depleted uranium used in the tests.

Table 13-3. Annual dose to the SW-MEI from explosives experiments on firing tables at Site 300, 1990–1998, related to the total quantity of depleted uranium used in the experiments and the total quantity of high explosives (HE) driving the detonations.

Year	Dose to SW-MEI (μSv)	Dose to SW-MEI (mrem)	Total depleted U used in experiments (kg)	Total HE used in depleted U experiments (kg)
1998	0.19	0.019	230	192
1997	0.11	0.011	163	122
1996	0.33	0.033	272	112
1995	0.20	0.020	165	199
1994	0.49	0.049	230	134
1993	0.11	0.011	99	74
1992	0.21	0.021	151	360
1991	0.44	0.044	221	330
1990	0.57	0.057	340	170

Table 13-4 lists the facilities that were primarily responsible for the LLNL dose; the contributions from all emission points at each facility have been summed. These facilities collectively accounted for approximately 97% of the total EDE resulting from Livermore site operations and for more than 99% of the total EDE from Site 300 operations. The principal radionuclide(s) are indicated for each facility. Tritium was the overall dominant radionuclide at the Livermore site, accounting for more than 93% of the Livermore site dose. At Site 300, practically the entire dose was attributed to the isotopes present in depleted uranium having atomic numbers 238, 235, and 234.

The relative significance of inhalation and ingestion is different for tritium and uranium and depends on the assumptions made about the origin of food consumed by a person receiving the dose. For the conditions we assumed when assessing individual doses, namely that milk is imported while the remainder of the food is produced locally, ingestion dose is larger than inhalation dose in the case of tritium, approximately in

the ratio 80% to 20%. For uranium, these numbers are nearly reversed: 17% by the ingestion pathway, versus 83% via inhalation. For both uranium and tritium, external doses from air immersion and ground irradiation were negligible.

Table 13-4. Major contributors to LLNL's radiation dose via airborne emissions, 1998.

Facility or operation[a]	Dominant radionuclide(s)	EDE at SW-MEI[b]	
		μSv/y	mrem/y
Livermore site			
B331/Tritium Facility	^{3}H	0.23[c]	0.023[c]
B612 Yard Area[d]	^{3}H	0.19	0.019
B331 Waste Accumulation Area[d]	^{3}H	0.039	0.0039
B177, U-AVLIS	^{238}U, ^{234}U, ^{235}U	0.015	0.0015
Sum of all other sources	Various	0.016	0.0016
Total		**0.49[c,e]**	**0.049[c,e]**
Site 300			
B801/firing table	^{238}U, ^{234}U, ^{235}U	0.17	0.017
Soil resuspension[d]	^{238}U, ^{234}U, ^{235}U	0.053	0.0053
B851/firing table	^{238}U, ^{234}U, ^{235}U	0.019	0.0019
Total		**0.24[e]**	**0.024[e]**

a The facilities cited here are discussed in the text of this report and in more detail in the NESHAPs annual reports.

b These doses represent the sum of all emission points from a given facility (for example, both stacks on Building 331), in contrast to the dose values in Table 13-1, which represent the dose from the single largest emission point at each facility. The site-wide maximally exposed individual (SW-MEI) member of the public is defined in the section on Identification of Key Receptors.

c Calculating dose as directed by EPA yields 0.29 μSv/y for the Tritium Facility, which raises the total dose to 0.55 μSv/y. (See the section Assessment Assumptions Regarding Tritium.)

d Diffuse sources (see text).

e These Livermore site and Site 300 totals represent 0.49% and 0.24%, respectively, of the federal standard.

Temporal Trends in Dose to the SW-MEI

The trends in dose to the SW-MEI from emissions at the Livermore site and Site 300 over the last nine years are shown graphically in **Figure 13-1** (see also **Table 13-2**). The general pattern, particularly over the last seven years, shows year-to-year fluctuations around a quite low dose level, staying at or below about 1% of the federal standard.

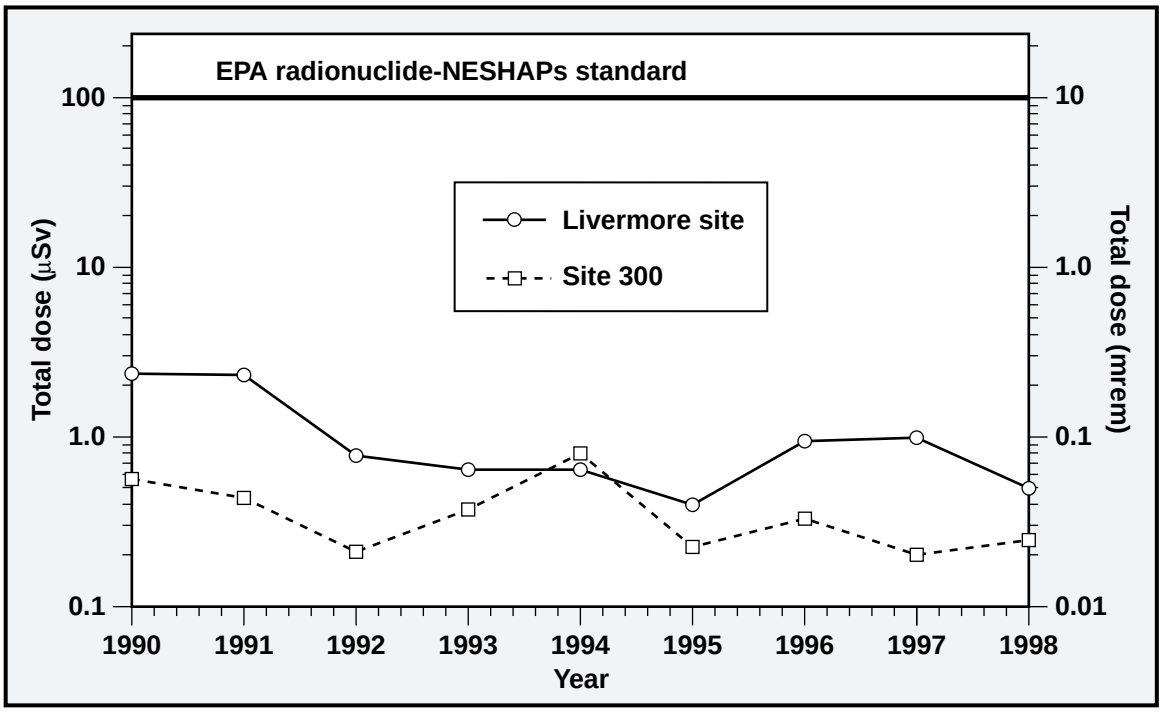

Figure 13-1. Dose to the site-wide maximally exposed individual member of the public, 1990 to 1998.

The SW-MEI dose estimates we report are intentionally conservative, erring on the side of predicting potential doses that are several times higher than would actually be experienced by any member of the public. Our potential doses from Site 300 firing table operations are especially so, as explained in the section on Special Modeling Problems.

Collective Doses to Exposed Populations

Population doses, or collective EDEs, for both LLNL sites were calculated out to a distance of 80 km in all directions from the site centers using CAP88-PC. For releases of radionuclides to air, CAP88-PC evaluates the four principal exposure pathways: ingestion through food and water consumption, inhalation, air immersion, and irradiation by contaminated ground surface.

The collective EDE caused by 1998 Livermore site operations was 0.68 person-rem (0.068 person-Sv), less than half of the 1997 result of 1.5 person-rem (0.015 person-Sv). Dose, when calculated as directed by EPA, was 0.84 person-rem (0.084 person-Sv). The corresponding collective EDE from Site 300 operations in 1998 was 11 person-rem

(0.11 person-Sv), which exceeds the previous year's value of 7.2 person-rem (0.072 person-Sv) by about 1.5 times. These levels of variation in population dose from one year to the next are within the expected range of operations-driven fluctuations in small radiation quantities.

Table 13-5 compares background and medical-treatment-related doses to the maximum potential doses caused by LLNL operations. The population doses attributed to LLNL operations are some 200,000 times smaller than ones from natural background radiation, and the maximum potential individual doses to maximally exposed public individuals from Livermore site and Site 300 operations are more than 6000 times smaller.

Table 13-5. Comparison of background (natural and man-made) and LLNL radiation doses, 1998.

Location/Source	Individual dose[a]		Population dose[b]	
	(μSv)	(mrem)	(person-Sv)	(person-rem)
Livermore site sources				
Atmospheric emissions	0.49[c]	0.049[c]	0.0068[c]	0.68[c]
Site 300 sources				
Atmospheric emissions	0.24	0.024	0.11	11
Other sources[d]				
Natural radioactivity[e,f]				
Cosmic radiation	300	30	1,900	190,000
Terrestrial radiation	300	30	1,900	190,000
Internal (food consumption)	400	40	2,500	250,000
Radon	2000	200	12,500	1,250,000
Medical radiation (diagnostic procedures)[f]	530	53	3,300	330,000
Weapons test fallout[f]	11	1.1	68	6,800
Nuclear fuel cycle	4	0.4	25	2,500

a For LLNL sources, this dose represents that experienced by the site-wide maximally exposed individual member of the public.

b The population dose is the collective (combined) dose for all individuals residing within an 80-km radius of LLNL (approximately 6.3 million people for the Livermore site and 5.4 million for Site 300), calculated with respect to distance and direction from each site.

c Calculating dose as directed by the EPA, the individual dose is 0.55 μSv (0.055 mrem), and the population dose is 0.0084 person-Sv (0.84 person-rem); see the sections on Doses to Site-Wide Maximally Exposed Individuals, and Collective Doses to Exposed Populations.

d From National Council on Radiation Protection (NCRP 1987a and b).

e These values vary with location.

f This dose is an average over the U.S. population.

Summary and Conclusion

The annual radiological dose from all emissions at the Livermore site and Site 300 in 1998 was found to be well below the applicable standards for radiation protection of the public, in particular the NESHAPs standard. This standard limits to 100 μSv/y (10 mrem/y) the EDE to any member of the public, arising as a result of releases of radionuclides to air from DOE facilities. Using EPA-mandated computer models, actual LLNL meteorology, and population distributions appropriate to the two sites, the dose to the LLNL site-wide maximally exposed members of the public from 1998 operations were as follows:

- Livermore site: 0.49 μSv (0.049 mrem)—52% from point-source emissions, 48% from diffuse-source emissions, using LLNL's standard calculational assumptions. Calculating dose as directed by the EPA, the total annual dose to the SW-MEI from Livermore site operations is 0.55 μSv (0.055 mrem), divided 57% by 43% between point and diffuse sources.
- Site 300: 0.24 μSv (0.024 mrem)—78% from explosive experiments, classified as point-sources, 22% from diffuse-source emissions.

The major radionuclides accounting for the doses were tritium at the Livermore site and the three isotopes in depleted uranium (^{238}U, ^{235}U, and ^{234}U) at Site 300.

The collective effective dose equivalent or population dose attributable to LLNL operations in 1998 was estimated to be 0.0068 person-Sv (0.68 person-rem) for the Livermore site and 0.11 person-Sv (11 person-rem) for Site 300. Calculating dose as directed by the EPA, the Livermore site number is 0.84 person-rem (0.084 person-Sv). These doses include exposed populations of 6.3 million people for the Livermore site and 5.4 million for Site 300 living within a distance of 80 km from the site centers, based on 1990 census data.

The dose to the maximally exposed member of the public resulting from Livermore site and Site 300 operations is seen to be about 6000 times smaller than the dose from background radiation, and the population dose from LLNL operations is about 200,000 times smaller than that caused by natural radioactivity in the environment (see **Table 13-5** and **Figure 13-2** in **Supplement 13-1** below).

We conclude that the potential radiological doses from LLNL operations were well below regulatory standards and very small compared to doses normally received by these populations from natural background radiation sources, even though highly conservative assumptions were used in the determinations of LLNL doses. These maximum credible doses indicate that LLNL's use of radionuclides had no significant impact on public health during 1998.

Chapter 13 Supplements

Supplement 13-1: Radiation Basics

Natural and man-made radiation. By far the greatest part of radiation received by the world's population comes from natural sources—primarily cosmic rays that impinge on the earth's atmosphere from space and radionuclides naturally present in our environment, such as radioactive materials in soil and rocks. Among these terrestrial sources are carbon-14, potassium-40, rubidium-87, uranium-238, thorium-232, and radioactive elements, such as radon, that arise from decay of uranium and thorium. The source of human exposure to natural radiation can be external (from substances staying outside the body) or internal (from substances inhaled in air or ingested in food and water). Individual doses vary with location. The level of cosmic radiation increases with altitude, because there is less air overhead to act as a shield, and the earth's poles receive more cosmic radiation than the equatorial regions, because the earth's magnetic field diverts the radiation. The levels of terrestrial radiation differ from place to place around the United States and around the world, mainly owing to variations in soil and rock composition.

Adding to this pervasive natural or background radiation is man-made radiation from radionuclides used in medicine, consumer products, the production of energy, and the production of nuclear weapons. Exposure to man-made sources can be controlled more readily than exposure to most natural sources. However, nuclear explosives tested in the atmosphere in the 1950s and 1960s spread radioactivity across the surface of the globe, and the nuclear reactor accident at Chernobyl in 1986 affected a large area. At present, medical treatment is the largest common source of public exposure to man-made radiation. Individual medical doses vary enormously—someone who has never had an x-ray examination may receive zero medical dose while patients undergoing treatment for cancer may receive many thousands of times the annual average dose they would receive from natural radiation. Another source of public exposure to man-made radiation is consumer products, including luminous-dial watches, smoke detectors, airport x-ray baggage inspection systems, and tobacco products.

Radioactivity. Generally, naturally occurring isotopes are stable, but notable exceptions include carbon-14, potassium-40, thorium-232, uranium-235, and uranium-238, which occur naturally but are radioactive. Nuclear decay divides into three main categories: alpha, beta, and gamma. Alpha decay is the spontaneous emission of an alpha particle (a bound state of two protons and two neutrons—the nucleus of a helium atom) from a nucleus containing a large number of protons (most commonly 82 or

more). Beta decay is the spontaneous conversion of a neutron to a proton in the nucleus with the emission of an electron, and gamma decay is the spontaneous emission of high-energy photons (high-frequency electromagnetic radiation) by nuclei.

Radioisotopes decay at quite different rates; the "half-life," or length of time for half of the atoms to decay, spans a wide range from small fractions of a second to millions of years. For example, tritium (the radioactive form of hydrogen) has a 12.3-year half-life, compared to 24,131 years for plutonium-239.

Some radioisotopes decay by forming radioisotopes that in turn decay into other radioisotopes until a stable state is achieved. For example, an atom of uranium-238 can undergo alpha decay, leaving behind a daughter, thorium-234, which is also radioactive. The transformations of the decay chain continue, ending with the formation of lead-206, which is a stable isotope.

Radioactivity can be hazardous because radiation (alpha particles, beta particles, gamma rays, and other subatomic particles such as neutrons) can be released with great energy. This energy is capable of altering the electronic configuration of atoms and molecules, especially by stripping one or more electrons off the atoms of the irradiated material, thereby disrupting the chemical activity in living cells. If the disruption is severe enough to overwhelm the normal restorative powers of the cell, the cell may die or become permanently damaged. Cells are exposed to many naturally occurring sources of disruption, including naturally toxic chemicals in food, microbes that cause disease, high-energy radiation from outer space (cosmic rays), and heat and light (including the sun's rays, which can cause sunburn and skin cancer). Consequently, cells and living organisms have evolved the capacity to survive limited amounts of damage, including that caused by radioactivity.

Three main factors determine the radiation-induced damage that might be caused to living tissue: the number of radioactive nuclei that are present, the rate at which they give off energy, and the effectiveness of energy transfer to the host medium, i.e., how the radiation interacts with the tissue. Alpha radiation can be halted by a piece of paper and can scarcely penetrate the dead outer layers of skin. Radioisotopes that give off alpha radiation are generally not health hazards unless they get inside the body through an open wound or are ingested or inhaled. In those cases, alpha radiation can be especially damaging because its disruptive energy can be deposited within a small distance, resulting in significant energy deposition in a few cells. Beta radiation from nuclear decay typically penetrates a centimeter or two of living tissue. It therefore deposits energy over many cells, decreasing the damage to any single cell. Gamma

radiation is extremely penetrating and can pass through most materials, only being significantly attenuated by thick slabs of dense materials, such as lead.

Measurement of Radioactivity and Dose. The rate at which a nucleus decays is expressed in units of becquerels, abbreviated Bq, where 1 becquerel is one decay per second, or alternatively in curies, Ci, where 1 curie equals 3.7×10^{10} (37 billion) decays per second, or 3.7×10^{10} Bq (approximately equal to the decay rate of 1 gram of pure radium). Becquerels and curies are not measures of the effect of radiation on living tissue. This depends on the efficiency of energy deposition as the radiation traverses matter.

The amount of energy deposited in living tissue is called the "dose." The amount of radiation energy absorbed per gram of tissue is called the "absorbed dose" and is expressed in units of rads or grays (Gy), where 1 Gy equals 100 rads. Because an absorbed dose produced by alpha radiation is more damaging to living tissue than the same dose produced by beta or gamma radiation, the absorbed dose is multiplied by a quality factor to give the dose equivalent. The quality factor for alpha radiation is 20; for beta and gamma, 1. The dose equivalent is measured in units of rem or sieverts (Sv); 1 Sv equals 100 rem. Also commonly used are millirem (mrem) and the millisievert (mSv), which are one-thousandth of a rem and sievert, respectively.

Just as one type of radiation can be more damaging than others, some parts of the body are potentially more vulnerable to radiation damage than others, so the different parts of the body are given weightings. For example, a given radiation dose from iodine-131 is more likely to cause cancer in the thyroid than in the lung. The reproductive organs are of particular concern because of the potential risk of genetic damage. Once particular organs are weighted appropriately, the dose equivalent becomes the "effective dose equivalent" (EDE), also expressed in rem or sievert. This allows dose equivalents from nonuniform exposure of the body to be expressed in terms of an EDE that is numerically equal to the dose from uniform exposure of the whole body that entails the same risk as the nonuniform exposure.

The EDE describes doses to individuals. When individual EDEs received by a group of people are summed, the result is called the "collective effective dose equivalent," often referred to as the "population dose," and is expressed in person-sievert or person-rem. Finally, to account for the long-term effects of radionuclides as they continue to decay and affect generations of people, we calculate the dose over many years, summing the effect over time. This is termed the "collective effective dose equivalent commitment." Most of our discussion in this chapter deals with the EDE and the collective effective dose equivalent.

Doses from Natural and Man-Made Radioactivity. The pie chart in **Figure 13-2** illustrates the distribution of annual average radiation doses from natural and other common sources in the United States, according to the National Council on Radiation Protection and Measurement (1987b). The average radiation dose from natural sources is 3.0 mSv / y (300 mrem / y). Approximately 0.3 mSv / y (30 mrem / y) of this exposure comes from high-energy radiation from outer space (cosmic rays). Terrestrial sources, mainly radionuclides in rock and soil, also account for approximately 0.3 mSv / y (30 mrem / y) of the average natural dose. Another significant part of the dose comes from radionuclides we ingest through food and drink, resulting in approximately 0.4 m Sv / y (40 mrem / y). Potassium-40 and carbon-14 are common radionuclides in food.

The remaining 2.0 mSv / y (200 mrem / y) or 67% of the average dose from natural sources in the United States comes from radon gas. Radon is one of the major radionuclides produced by uranium decay, and our inhalation dose is dominated by radon's short-lived decay products.

We noted earlier that medical treatment is the largest common source of public exposure to man-made radiation, and most of it is delivered as medical x-rays. These contribute 0.39 mSv (39 mrem) to the average whole-body annual dose in the United States. Nuclear medicine contributes 0.14 mSv (14 mrem) to the average dose, and consumer products add 0.1 mSv (10 mrem). Thus, for a typical member of the public in the United States, radiation from medical procedures and consumer products result in a dose of approximately 0.63 mSv / y (63 mrem / y). The annual average dose from other man-made sources, including fallout from nuclear testing, is less than 0.03 mSv (3 mrem). As described in this chapter, the contributions from LLNL operations to the dose of even the most affected resident are on the order of 1 μSv / y (0.1 mrem / y) or less and would not be discernible on the scale shown in **Figure 13-2**; LLNL's contributions are listed under "Other" in the figure.

Deviations from the average levels shown in **Figure 13-2** can be quite large, depending on an individual's place of residency, occupation, eating habits, and other lifestyle choices, such as inclination to air travel. Radon dose, for example, varies significantly with geographic location; levels several times higher than the average occur in some regions of the United States, while at LLNL and its environs randon-induced doses as low as half the average are typical. Doses from cosmic rays increase with elevation above sea level, producing several tenths of mSv (tens of mrem) differences between cosmic ray doses in coastal and mountain communities, and imparting a dose of about 0.05 mSv (5 mrem) to a passenger flying round-trip between Los Angeles and New York City.

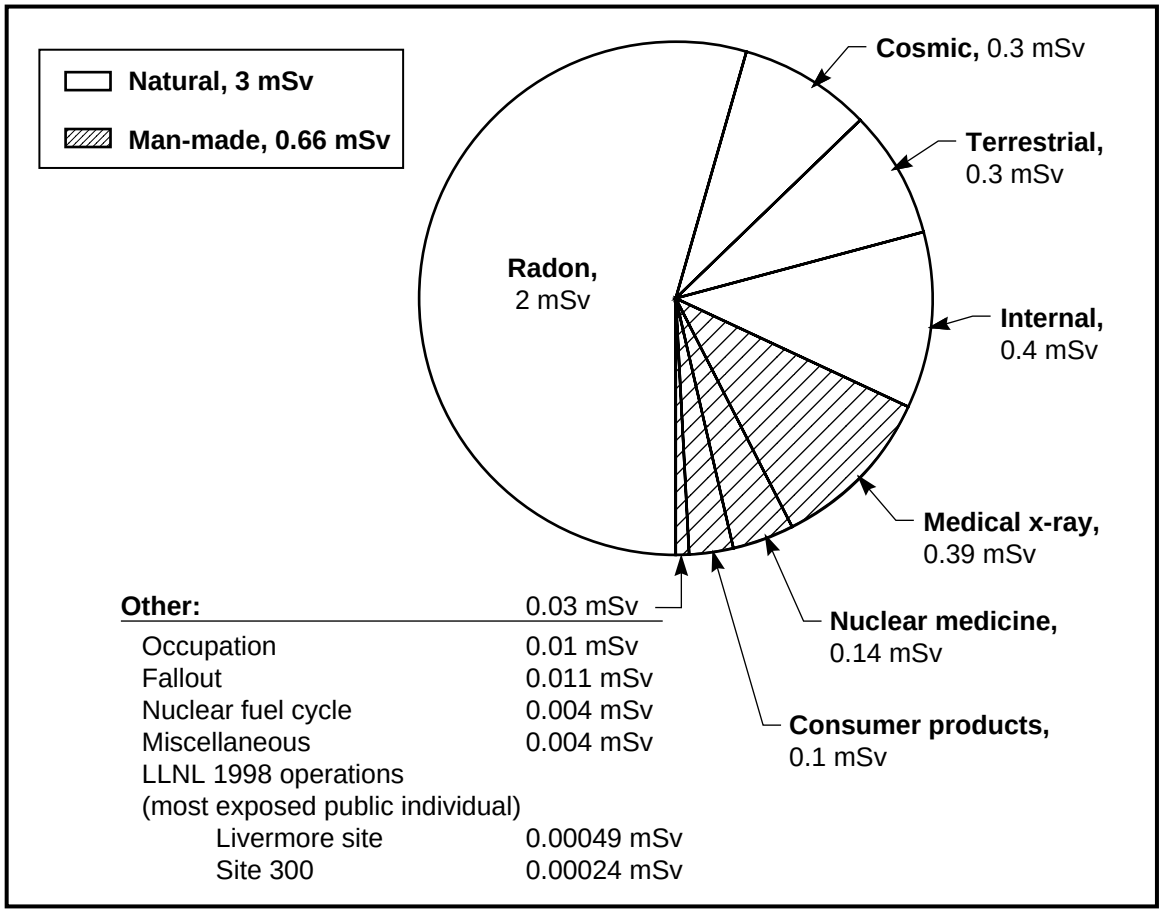

Figure 13-2. Typical annual radiation doses from natural and man-made sources (National Council on Radiation Protection 1987b).

For further reading, a useful Internet reference offering multiple linkages to a large quantity of interesting and educational material on effects and risks from radiation is the "Radiation Information Network" at the address http://www.physics.isu.edu/radinf/qanda.htm.

Supplement 13-2: Radiation Control Measures at LLNL

Radioisotopes used at LLNL include uranium, transuranics, biomedical tracers, tritium, and mixed-fission products. Protection of employees and the public from the uncontrolled release of radioactive materials into the environment is a primary consideration for LLNL. This effort takes several forms, as summarized here.

13 Radiological Dose Assessment

When an operation or facility is designed, a thorough assessment of potential radiation hazards is conducted, and radioisotope-handling procedures and work enclosures are determined for each project, depending on the isotope, the quantity being used, and the type of operations being performed. Radioisotope handling and working environments include glove boxes, exhaust hoods, and laboratory bench tops. The controls might include limiting physical access and using shielding, filters, and remote handling equipment. Exhaust paths to the atmosphere include HEPA-filtered stacks, stacks lacking abatement devices, roof vents, and ordinary room air ventilation channels. Facility safety analysis reports and facility safety plans are written to document the need for specific measures and to spell out the requirements for maintenance, training, emergency response, and other administrative control measures.

When a facility is occupied for use, an operational safety plan (OSP) is written that specifies actions to be taken in conducting a research or development project. This procedure is reviewed by environmental analysts, industrial hygienists, and health physicists to assess the safety of the operation, its compliance with current occupational health and environmental standards, and the adequacy of proposed engineering and administrative controls. The OSP also specifies training requirements for personnel. This part of the control program enables LLNL personnel who work with radiation and radioactivity to recognize and prevent the execution of unsafe operations.

Another form of LLNL's radiation control program involves direct monitoring of the workplace environment. This includes sampling of the air and surfaces in facilities where radioactive materials are handled, and includes personal dosimetry and bioassay programs used to monitor potential worker exposure to direct radiation and radioactive isotopes. This monitoring program helps to determine the effectiveness of a facility's radiation control program as well as providing information on worker exposures.

The surveillance and effluent monitoring of radiation in air, ground and surface waters, sewerable water, soil and sediment, and vegetation and foodstuff, as discussed in Chapters 2 and 4 through 11 of this report, play an important role in LLNL's program to control radiation releases. These measurements can signal anomalous releases, should they occur, and directly gage the degree of success of LLNL's radionuclide discharge control program in limiting exposures of the public.

Development of the Livermore Valley and the San Joaquin Valley has enlarged the populations and decreased the distance between sources of emissions and the residents who might be exposed. People live and work within several hundred meters of LLNL's boundaries. It is therefore increasingly important that our assessments provide the best information possible regarding the radiological impact of LLNL operations.